

Electromagnetic Launch Vehicle Fairing and Acoustic Blanket Model of Received Power using FEKO

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Abstract — Evaluating the impact of radio frequency transmission in vehicle fairings is important to electromagnetically sensitive spacecraft. This study employs the multilevel fast multipole method (MLFMM) from a commercial electromagnetic tool, FEKO, to model the fairing electromagnetic environment in the presence of an internal transmitter with improved accuracy over industry applied techniques. This fairing model includes material properties representative of acoustic blanketing commonly used in vehicles. Equivalent surface material models within FEKO were successfully applied to simulate the test case. Finally, a simplified model is presented using Nicholson Ross Weir derived blanket material properties. These properties are implemented with the coated metal option to reduce the model to one layer within the accuracy of the original three layer simulation.

Index Terms — FEKO, MLFMM, Nicholson Ross Weir, Resonant Cavity.

I. INTRODUCTION

With multiple contributions from the range and surrounding radio frequency (rf) emitters, defining the electromagnetic environment for spacecraft can be a daunting task [1]. Determining the environment inside the vehicle fairing presents further challenges as field distribution within the cavity is influenced by resonances which require a full wave solution to achieve the desired accuracy.

An added concern is that most spacecraft transmitters are in the GHz frequency range making the structures electrically large and memory requirements a constraint for many of the 3D electromagnetic simulation tools available.

In this paper, two cases are evaluated: a three layer model, and a one layer model. The three layer model of a vehicle fairing with layered acoustic blanketing materials characterized by thin surface approximations is first presented [2]. For comparison and validation purposes the test case [3] is summarized here and used as evaluation data. Finally, an equivalent one-layer model is developed using material properties predicted with S-parameters measurement and implemented in to FEKO standard coating option.

II. FAIRING FIXTURE

A computational fluid dynamics fairing test fixture was modified by lining the Lexan outer shell with industry grade aluminum foil [4]. The fairing has three sections bolted together and a metal frame outer support structure. This fixture is representative of typical launch vehicles, although at a smaller scale with a height of 2 meters and a diameter of 0.6 meters. The aluminum lined fairing fixture is shown in Fig. 1. Transmit and receive double ridge guide horns were placed at the bottom and top of the fairing fixture, respectively [5].

Lining materials were added to the inside of the test fixture to simulate typical acoustic blankets inside vehicle fairings. Kapton is

commonly used in space applications for its favorable thermal insulating properties. DuPont's Kapton 160XC, designed to maintain a surface resistance of 377 ohms with inherent RF absorption properties, is utilized as the outer blanket layers while standard ½ inch foam is used as the internal layer.

The test results from this fairing fixture with acoustic blanketing are used for comparison with the three layer and one layer models presented here. The goal is to obtain an equivalent one layer model that has similar test data correlation as the three layer model.

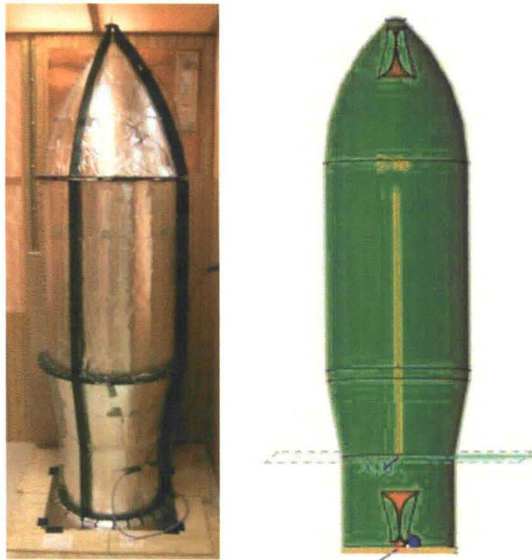


Fig. 1. Test fixture with CAD model.

III. THREE LAYER MODEL

A commercial computational electromagnetic software tool, EM Software Systems, FEKO is utilized in this study. The multilevel fast multipole method (MLFMM) feature is implemented to extend the method of moments (MoM) technique to higher frequencies. As MLFMM is an iterative technique that relies on convergence to a specified error, accuracy comparisons were made. Figure 2 demonstrates the adequacy of this approach for an aluminum cavity represented by an impedance sheet with both MoM and MLFMM techniques. The field

distribution and power received at 1 GHz using a surface impedance of 0.015 ohms reveals excellent agreement.

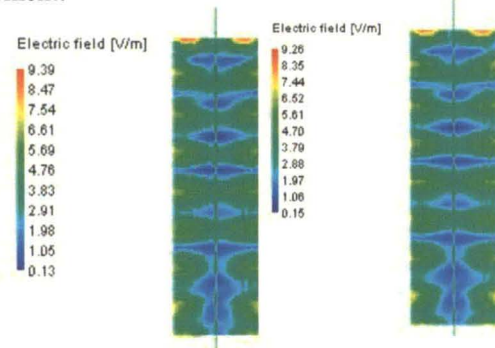


Fig. 2. Field distribution of aluminum fairing – MLFMM and MoM.

Similar results were found with FEKO's lossy metal feature which has minimal computational penalties compared to the efficiency of a perfect electric conductor (PEC). FEKO evaluates the input material properties, such as permittivity and conductivity, to obtain a representative impedance term, Z_s , which is then added to the standard electric field integral equations used for PEC structures as in (1) [6,7].

$$E_{s,tan} - Z_s J_s = -E_{i,tan} \quad (1)$$

Where,

\vec{E}_i is the field due to an impressed source in the absence of the scatterer

\vec{E}_s is the scattered field

J_s is the equivalent current density

Antenna pattern models presented in [2] of the EMCO 3115 horn developed within FEKO are implemented in this simulation. Replacing the horn model with the horn pattern affords a significant savings in computational resources. Parallelization of the FEKO code via pre-conditioners, such as the sparse approximate inverse, supports solutions for detailed electrically large structures as presented here [8].

A combined blanketing and composite fairing structure model was presented in [9]. In this paper, it is desired to first represent the layers separately for direct test comparison. Fig. 3 depicts the test fixture layers and the composite model within FEKO.

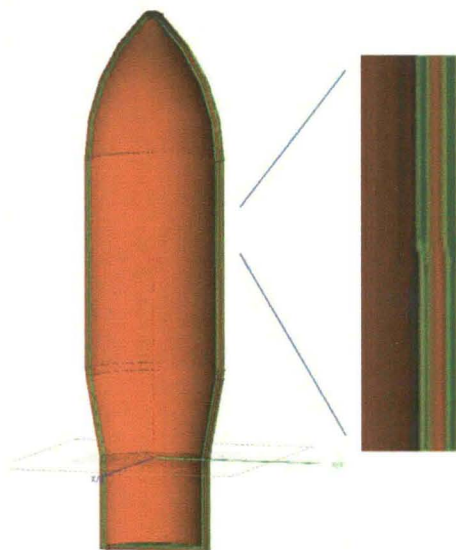


Fig. 3. FEKO model with acoustic blankets.

The aluminum foil outer layer and acoustic blanketing layers were represented within FEKO as described below:

- The fairing outer walls were represented as a single layer lossy metal with a thickness representing the industry aluminum foil that lined the prototype fairing (0.127 mm thick).
- Kapton sheets are modeled with a surface impedance based on industry data at the model frequency.
- Gaps between the impedance sheets represent the foam layer.
- Free space is required on both sides of the impedance sheet thus a thin layer of free space is implemented between the Kapton and aluminum.

Test to computational model comparisons presented in Fig. 4 show favorable results over the frequency range considered. The average variation was 2.43 dB from test data. This is reasonable for a test article to model comparisons given uncaptured variations in test set-up. Selection of this frequency range is related to the supporting data availability for future work comparisons.

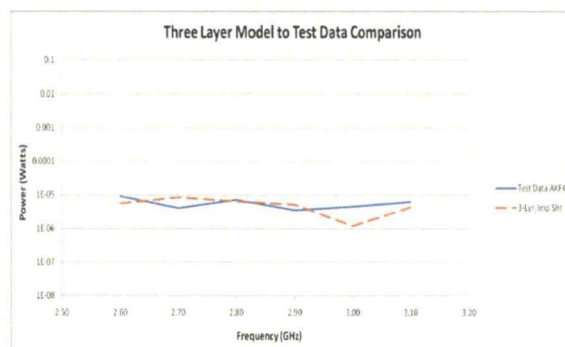


Fig. 4. Acoustic blanket model to test comparison.

IV. EQUIVALENT ONE LAYER MODEL

It is desirable to further reduce the required computational resource and run-time requirements of the three layer simulation by using an equivalent one layer model. Another reason to form a one layer equivalent model is the limited availability of vehicle CAD models with blanket configuration information.

A. Methodology selection

Truncation of the scalar Green's function implemented with the addition theory series in MLFMM introduces an error that can be controlled in open structures, but difficult to achieve sufficiently accurate results in electrically large reflective cavities [10]. This residual error can, in effect, numerically excite the cavity. Thus, convergence is improved by using layer representations that characterize the material absorption. The absorbing impedance sheets used in the three layer model require a layer of free space on either side; consequently, the one layer model requires a different material representation that can model readily be combined with the metallic outer layer. The difficulty in representing the entire vehicle in one layer is the contrast between the aluminum properties and that of the acoustic blankets. Accordingly, an option was used to apply the blanket properties as a coating to the metal outer layer. Material properties of the lossy metals and dielectrics are represented in the FEKO material tree. Dielectrics are then selected in a thin dielectric sheet (TDS) with specified thickness. Coatings are selected from the TDS single layer options. The TDS is implemented

within FEKO in a similar way as the impedance sheet in (1) with the Z_s term described in (2) [6].

$$Z_s = \frac{1}{j\omega(\epsilon_2 - \epsilon_1)d} \quad (2)$$

A TDS is required to be geometrically or electrically thin (approximately 1/10 the smallest element or wavelength respectively). Due to the geometric constraint, a dominant limitation is often encountered as the automatic mesh routine generates fine elements to accurately characterize respective geometries. However, if the coating is geometrically small with respect to the majority of the elements, the geometric constraint is effectively ignored in the solution. A FEKO utility will perform a validate check, and only warnings will be returned in the solution. It is also important to note that the electrically thin constraint is relative to a wavelength in the interfacing medium, but the layer does not have to be electrically small relative to a wavelength of the layer itself [7]. Nevertheless, it is often the situation that the actual thickness of the blankets cannot be represented in the coating, and an equivalent method must be demonstrated and evaluated.

B. Sample s-parameter measurement

The one layer coating constraint drives the need to represent the three layer blanket model in the waveguide with a one layer TDS. The Nicholson Ross Weir (NRW) technique is used to derive an equivalent permittivity of the entire layered blanket using s-parameter measurements. A blanket sample was placed in an S-Band waveguide. The s-parameters are then measured with a vector network analyzer as in Fig. 5. These parameters are then evaluated in expression (3) to provide an approximation of an equivalent permittivity of a homogenous sample of the same length. As most launch vehicle blanketing materials are non-magnetic, setting the permeability, μ_r , to one simplifies the permittivity determination. Moreover, TDS implementation requires the permeability to be continuous with the surrounding media.

$$\epsilon_r = \frac{\lambda_0^2}{\mu_r} \left(\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L} \ln \left(\frac{1}{T} \right) \right]^2 \right) \quad (3)$$

Where, λ_0 is the freespace wavelength for the desired frequency, λ_c is the waveguide cut-off wavelength, L is the sample length, and T is the transmission coefficient determined by the measured S-parameters [11].



Fig. 5 Material sample test fixture.

Determining the permittivity of a homogeneous sample using waveguide measurements and computational models has been verified as effective in the literature [12]. In this paper, the NRW technique is used to determine a first level approximation of an equivalent permittivity that would apply to a dielectric block with the same measured s-parameters, although the sample itself is layered. Full wave analysis is then used to modify the permittivity at each frequency until a sufficiently close approximation of the s-parameters is found. This equivalent permittivity data is then used to construct the coating in the vehicle one layer model.

C. Waveguide sample models

A three layer MoM model was first constructed in FEKO as shown in Fig. 6 to emulate the actual S parameter measurement set-up. The permittivity and conductivity of each Kapton layer was characterized as a dielectric with the thickness accounted for in the TDS implementation. The foam was represented by air as in the three layer vehicle model.

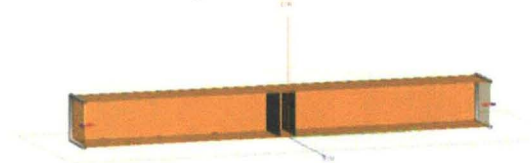


Fig 6. FEKO MoM model of vehicle blanket sample.

It is straight forward to convert the separate layer model into a multilayer TDS which only uses one face in the geometry representation. However, the multilayer TDS cannot be represented as a coating to a metal. Hence, representation of the material in a single TDS is pursued.

FEM was employed to verify that the NRW derived equivalent properties derived with (3) represent the S parameters when the waveguide is filled with a homogeneous dielectric block. The FEM model in Fig. 7 effectively reproduced the results as shown in Fig. 9 with some parameter optimization in the model. In this instance the regions defining the boundary of the block are represented as the dielectric material and implemented with permittivity parameters with respective loss tangents.

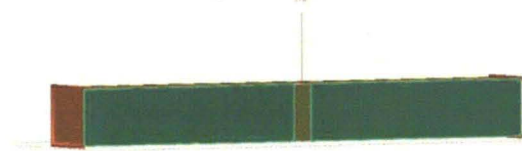


Fig 7. Equivalent homogeneous dielectric block.

The parameters were implemented with a TDS single layer as shown in Fig. 8 for final implementation into the vehicle fixture.

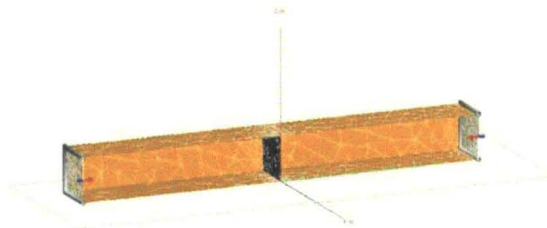


Fig 8. TDS layer in waveguide

When meshing constraints require a reduced thickness in the TDS layer, a thinner layer can be established by changing the sample length in (3) to achieve a corresponding permittivity. Fig 9. shows a comparison of test, MoM separate layer model, FEM dielectric block model and the final single layer TDS with original and reduced sample thicknesses. Variation of the material parameters can then be exercised to provide a closer match to the original S21 measurements.

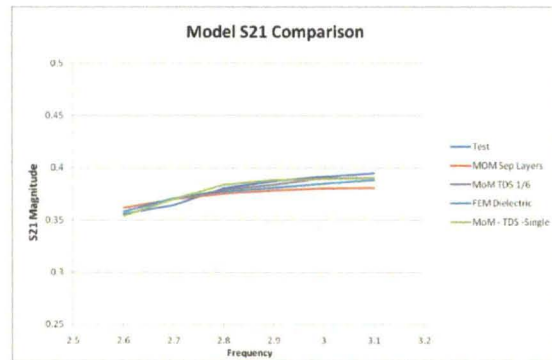


Fig. 9. Waveguide S-parameter test data compared to FEKO models

D. Equivalent one-layer vehicle model

Results in Fig 10 shows that incorporation of the permittivity and loss tangent derived from the NRW waveguide technique into a TDS coating of a single metal layer in the vehicle model provides a reasonable correlation to the test data, as does the 3 layer model. First, the original sample thickness results are applied directly to the coating properties. Due to layer wavelength related constraints, however, the thickness of the coating is set at 3 skin depths of the kapton layer. A closer approximation is achieved by using (3) to provide a different permittivity and loss tangent to correspond to a sample thickness adjusted to a smaller value. Results shown are for a TDS length of 1/6 of the original sample which varied from the test results an average of only 2.5 dB.

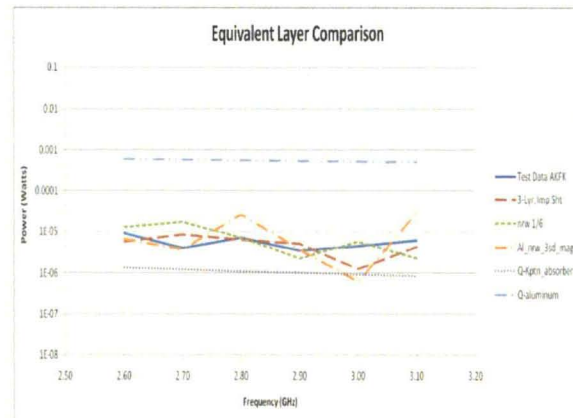


Fig. 10 Single and three layer vehicle model comparisons with test data.

The upper and lower bounds represented in fig 10 are based on cavity Q equations for aluminum and blanketed walls [13]. It is evident that the

FEKO models provide a significant improvement over relying on approximation results. It should be noted that the primary intent of the Q related approximations are to evaluate chambers with very conductive walls with small absorbers present, but the application of these equations are often extended cavities with more complex material configurations.

The efficiency benefits of using MLFMM in a three and one layer model as compared to MoM are shown in Table 1.

Table 1: Memory/Run Time Comparison

Method	Freq (GHz)	# unknowns	CPU Time/process (hrs)	CPU Time All processes (hrs)	Peak Mem All Processes (GB)
MoM 1 layer	2.6	124,377	21.2	339	115
MLFMM 3 layer	2.6	372,622	3.9	60.9	10
MLFMM 1 layer	2.6	124,377	.066	1.1	2.2

V. CONCLUSION

This paper shows that fairing structures with complex blanketing materials can be modeled effectively with equivalent impedance techniques in a multilayer MLFMM model within the FEKO solution environment. This is important because quantifying fields due to transmission within a vehicle fairing has largely relied on general reverberation chamber average power approximation. The techniques explored here were the three layer and one layer models. From this data set, both methods appeared to have an improvement over the power approximation techniques for a launch vehicle with simulated acoustic blankets. The equivalent one-layer approach utilized a novel application of NRW formulations to derive an equivalent permittivity of the three layer configuration. Future work includes extending the frequency range beyond S-Band and the application of this technique to other layered materials such as composite vehicle structures.

ACKNOWLEDGMENT

The testing of the blanketing layers was performed by Dr. Ellen Lackey and Dr. Elliott Hutchcraft from University of Mississippi.

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